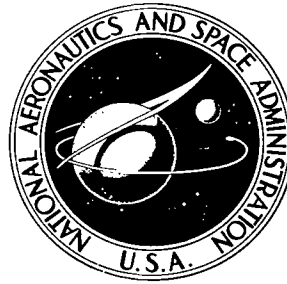


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DEVELOPMENT OF COLUMBIUM ALLOY WC3015

by A. A. Tavassoli

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| 16. Abstract The effect of changes in basic composition and additions of alloying elements on mechanical properties of columbium alloy WC3015 is reported. A 500-ppm addition of yttrium to the basic composition plus an anneal for 1 hr at 1093° C (2000° F) is shown to provide a superior combination of properties with a ductile-to-brittle transition temperature below -129° C (-200° F). Nevertheless, the oxidation resistance of WC3015 is shown to be inadequate for a typical reentry environment. The oxidation rate of WC3015 is shown to be parabolic at 1316° C (2400° F), resulting in an oxidation rate higher than Cb752, for times less than 40 min. It is concluded that since oxidation resistance obtained at the expense of ductility and elevated temperature strength is not justified for thermal protection system application, more emphasis should be placed on improving ductility, elevated temperature strength, and creep. Substitution of over 10 percent of the hafnium by tantalum and elimination of titanium are suggested for improving the above properties. | | | | | |
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DEVELOPMENT OF COLUMBIUM ALLOY WC3015

SUMMARY

The effect of changes in basic composition and additions of alloying elements on mechanical properties of columbium alloy WC3015 is reported. In general it is shown that WC3015 exhibits superior tensile strength over C129Y, Cb752, and FS85 at temperatures below 871°C (1600°F), but this superiority is rapidly decreased at higher temperatures. Additions of yttrium to the basic composition were found to have an improving effect on ductile-to-brittle transition temperature. However, even with yttrium additions, DBTT of WC3015 alloys exhibited marked dependence on final annealing temperature. Oxidation resistance of WC3015 was found to be superior to other primary candidates for longer than 40 min of exposure to 1316°C (2400°F); nevertheless, it was not as good as previously assumed. Major changes in composition of WC3015 are recommended for improved elevated temperature properties.

INTRODUCTION

An important technology area effecting development of the space shuttle is the thermal protection system (TPS). Preliminary designs show that aerodynamic heating during a typical reentry will raise the TPS temperature of the orbiter in some surface areas to the 1316°C (2400°F) temperature regime [1]. Fortunately, other reentry parameters, such as internal and external pressures or stresses, will not be at their peaks when maximum reentry temperature occurs. Typical reentry profiles show that the 1316°C (2400°F) temperature regime lasts for about 15 min and is then followed by a rapid cooling so that after 40 min the temperature is reduced to below 538°C (1000°F).

A close approximation to thermal protection system requirements may be 100 thermal exposures to 1316°C (2400°F) each for 20 min. Unfortunately, none of the present columbium primary alloy candidates (C129Y, Cb752, and FS85) has sufficient oxidation resistance to survive such exposures without heavy protective coatings. The problems associated with coated materials are many, and a large-scale coating failure could be catastrophic. Hence, it is highly desirable to use an oxidation resistant material that, at least, can survive one exposure to reentry environment.

The new columbium alloy WC3015 has been reported to have a superior oxidation resistance over the primary candidate materials [2] and is therefore the subject of special consideration for TPS application. The early test data on the properties of WC3015 were provided through cooperation with Mr. W. K. McDonald.¹ Nevertheless, the reported data represent the author's evaluation of the available results and may not correspond to those published by the manufacturer [2].

MATERIALS

The actual compositions of the main WC3015 heats (experimental ingots) that were investigated are shown in Table 1. The typical compositions of primary candidates C129Y, Cb752, and FS85 are also included in this table. Oxidation tests were carried out on WC3015 (heat 216) and Cb752 (heat 86D 1185).

RESULTS

Tensile Properties

The early test data on the initial WC3015 compositions are given in Table 2.¹ Tensile tests on the basic WC3015 composition (heat 066, 29Hf-14.5W-0.1C) showed that the as-extruded material with 1.27-cm (1/2 in.) diameter exhibits significant improvement in ductility over as-extruded material with 4.12-cm (1 5/8 in.) diameter. The ductility of the as-extruded material was further improved by 6 hr of annealing at 1316°C (2400°F), whereas annealing at higher temperatures [such as 1700°C (3200°F) for 1 hr] slightly lowered the total elongation. In most cases, the as-extruded material [1.27-cm (1/2 in.)] also showed a superior tensile strength. A 0.2 percent increase in carbon content, from heat 066 to heat 068, further increased tensile strength with no significant adverse effect on ductility. However, a marked reduction in total elongation was observed when titanium or/and aluminum additions were made to the basic WC3015 composition (heats 075, 078, and 081).

The next heat was prepared by reducing tungsten and almost eliminating carbon concentrations, heat 167 (29 Hf-13.3W-5Ti-1Zr). This alloy, when annealed 1 hr at 1093°C (2000°F), exhibited high strength and good ductility at room temperature but showed almost zero elongation at 982° to 1093°C

1. Private communication with Mr. McDonald, Wah Chang Corporation.

(1800° to 2000° F) (Figs. 1 through 3). Annealing at 982°C (1800° F) for 1 hr resulted in an increase in strength but reduced elongation to less than a third of the previous annealing temperature 1093°C (2000° F)/1 hr (Table 3).² Annealing temperatures higher than 1093°C (2000° F), such as 1399°C (2550° F), had a more severe effect on reducing elongation at both low and elevated temperatures. Increasing tungsten and hafnium concentrations, heat 183 (31Hf-15W-4.5Ti), also lowered elongation at room temperature but resulted in an extremely higher ultimate tensile strength (UTS) [38×10^7 N/m² (200 ksi)]. Nevertheless, the strength of the heat 183 rapidly decreased with increase in temperature, whereas ductility increased (Figs. 1 through 3). The marked loss observed in strength of the heat 183 at elevated temperatures was associated mainly with presence of 4.5 percent titanium. The heat 189 was prepared without the titanium (29Hf-15W-0-1Zr) addition. The samples of the heat 189 showed lower room temperature tensile strength and moderate ductility. Although the heat 189 exhibited superior elevated temperature tensile strength over the heat 183, it suffered from low elongation at 1093°C (2000° F) temperature regime. Similar responses to changes in composition were also exhibited by samples from the heats 191 and 201 (Figs. 1 through 3).

Finally, addition of 500-ppm yttrium to heat 201 (heats 216 and 230) significantly improved ductility of the material, and a continuous increase in elongation with temperature was recorded. The typical minimum in elongation at 871° to 1093°C (1600° to 2000° F) was eliminated. The interaction of yttrium with oxygen is probably the main factor for improved ductility of the heat 216. However, it was noticed that even the ductility of samples from the heat 216 was vulnerable to thermal heat treatment and that 2 hr at 1427°C (2600° F) (Table 3) introduced a minimum elongation at 1093°C (2000° F). In general, all the samples showed lower elongation in transverse direction than longitudinal, and this reduction was more marked when longitudinal elongation was of the order of 5 percent.

The tensile properties of FS85 [3] and Cb752 [4] are also shown in Figures 1 through 3. C129Y² shows slightly superior tensile properties to Cb752, and both Cb752 and C129Y will occupy more favorable positions on tensile figures (Figs. 1 through 3) if the density compensated strength is plotted against temperature.

2. Ibid.

Ductile-to-Brittle Transition Temperature (DBTT)

Bend angle versus temperature for several WC3015 compositions is given in Table 4.³ Most of the test pieces were 0.508 mm (0.020 in.) thick, and those that were 0.76 mm (0.030 in.) to 1.17 mm (0.040 in.) are indicated with a star. The DBTT of WC3015 heats was found to be critically dependent on final annealing temperature. For instance, samples from the heat 066 (27Hf-14.5W-0.1C) exhibited a higher bend angle at room temperature when annealing temperature was raised from 982° to 1316°C (1800° to 2400°F). Samples from the heats 068 (30Hf-14W-0.3C) and 167 (29Hf-13W-5Ti) showed a larger bend angle when annealed at 1204°C (2200°F) or 1093°C (2000°F), respectively, than 1316°C (2400°F).

A significant improvement in DBTT of the heat 201 (28Hf-15W-4Ti-0.1C) was also achieved by small additions of yttrium (heat 216). The marked lowering of DBTT by yttrium addition is attributed to its ability to trap oxygen atoms. Oxygen has been shown to have deteriorating effect on DBTT of columbium alloys, and most candidate alloys contain less than 100-ppm oxygen [5, 6]. Although it is very difficult to reduce the oxygen level of columbium alloys in commercial products below 100 ppm, it is believed that DBTT of WC3015 will be improved if lower oxygen concentrations are attained.

Substantial reductions in tungsten concentration, heat 191 (30Hf-10W-5Ti-0.1C), also improved DBTT; and a small addition of yttrium to the heat 191 is expected to further improve this factor.

Microstructural Investigations

A major problem associated with the WC3015 heats was a marked response of various heats to annealing temperature or time. To investigate this problem, samples from the heats 189, 191, 201, 216, and 230 were all annealed for 1 hr at 1093°C (2000°F) in vacuum. The samples were then mounted and etched in a solution of 28.6 percent hydrochloric acid, 28.6 percent nitric acid, 28.6 percent fluoric acid, and 14.2 percent water. The optical photomicrographs taken from these samples are shown in Figure 4. Although all the samples appear to have developed to some extent equi-axed new grains (recrystallized), only the sample from the heat 191 is free from heavy, wavy slip bands. The samples from the heats 216 and 201 appear to have less deformation bands than those from 189 and 230. In general, it can be concluded that tungsten has an increasing effect on the recrystallization temperature.

3. Ibid.

It is surprising that samples from the heat 230 appear to have retained more dislocations than those from the heat 216. The heat 230 was prepared with the intention to reproduce the same composition as 216; minor differences are only in oxygen and yttrium levels between the two heats. This discrepancy is probably caused by minor changes in prior working or heat treatment history of the samples rather than changes in compositions.

Oxidation Resistance

At the present time WC3015 is less ductile and formable than other primary columbium candidate alloys for TPS applications. Nevertheless, if this alloy could provide superior oxidation resistance, it might be a more favorable selection than other columbium alloys for TPS application. To examine the oxidation resistance of WC3015, two samples of WC3015 (heat 216) and two of Cb752 [all with $6.5 \times 1.27 \times 0.0508$ cm ($2.5 \times 0.5 \times 0.020$ in.) dimensions] were placed in a furnace at $1316^\circ \pm 3.6^\circ\text{C}$ ($2400^\circ \pm 5^\circ\text{F}$) in still air. After 4 hr the samples were removed from the furnace and, as Figure 5 shows, neither of the samples had survived this test. The Cb752 samples were split in half and WC3015 samples showed the start of such splitting. This behavior is largely caused by different levels of working through the thickness induced during rolling.

A similar test on the same size samples was carried out for 30 min, at 1316°C (2400°F), to determine how the alloys will behave during reentry in case of a large coating failure. WC3015 showed only a 3 percent weight gain and a small increase in width, whereas Cb752 showed a loss of greater than 40 percent in both weight and thickness. Nevertheless, optical microscopy revealed that Cb752 had retained a larger unoxidized material zone than WC3015 (Fig. 6). The effected depth across the WC3015 thickness was composed of a fully oxidized outer layer, similar to a smaller oxide layer left over Cb752 surface, and an extended depth that was partially oxidized. The latter area is probably the same adherent oxygen-rich region reported to occur on thicker WC3015 samples [2].

To determine which material will offer superior mechanical properties after 30 min of exposure, tensile test pieces of WC3015 (heat 216) and Cb752 were exposed to 1316°C (2400°F) in air. The Cb752 sample fractured during air cooling but was damaged less when it was furnace cooled, i. e. 15 min from 1316° to 871°C (2400° to 1600°F) and 15 min to room temperature. The WC3015 samples survived both cooling rates and only exhibited slight warping. Table 5 shows weight and tensile strength changes before and after

30 min of exposure to 1316°C (2400°F) for both cooling rates. Although Cb752 had lost over 50 percent of its weight after this exposure, it exhibited higher tensile strength than WC3015. Both alloys exhibited brittle fracture.

WC3015 has been reported to oxidize to a depth of 0.089 cm (0.035 in.) after 24 hr at 1316°C (2400°F) [2] and then to oxidize at a much slower rate. This type of oxidation is typical of materials showing parabolic resistance to oxide penetration. The general equation

$$X^2 = At + C \quad ,$$

where X is oxide penetration (mil), t is time (hr), and A and C are constants, was adjusted for WC3015 after several more tests to be:

$$X^2 = 77t + 33 \quad .$$

The data points of the oxidation test results for WC3015 and Cb752 are shown in Figure 7. This figure shows that WC3015 oxidizes more rapidly during the first 0.7 hr of exposure to 1316°C (2400°F) than Cb752, which is a less oxidation-resistant alloy at longer times. However, both alloys were brittle even after 5 min of exposure, indicating severe oxygen penetration.

The manufacturer,⁴ in response to this finding (Fig. 6), has carried out a 30-min exposure of WC3015, C129Y, and Cb752 to 1316°C (2400°F). The results indicated that all the alloys are embrittled; however, the anodized photomicrographs showed that the remnant material band in WC3015 (Fig. 6) is not affected, whereas the whole Cb752 material is affected by oxygen. Nevertheless, Figure 6, in particular if magnified, shows an extended oxide penetration along grain boundaries of the central band of WC3015, whereas the oxide penetration was far less in Cb752. An explanation for this discrepancy is the probable presence of a higher oxygen level in solid solution in Cb752.

The parabolic oxidation resistance of WC3015 can be beneficial in case of the growth in area of a small coating defect. For instance, Table 6 shows the oxidation tests carried out by the manufacturer⁴ on four coated WC3015 heats, C129Y and Cb752. A coating defect of 0.0102×0.636 cm (0.004×0.25 in.) was introduced by electrical discharge machining, and oxide penetration was measured in perpendicular directions to thickness. WC3015 apparently shows very good coatability by VH 112 and is at least

4. Ibid.

twice as good in oxidation resistance as C129Y or Cb752 coated with VH 109. It is expected that WC3015 will improve on its lead over primary columbium alloy candidates after longer exposure time because of its parabolic response.

CONCLUSIONS

The effect of alloying additions on the mechanical properties of columbium alloys had been reviewed previously in detail [5-7]. It has been shown that tungsten additions to columbium, not only have an increasing effect on tensile strength at both low and elevated temperatures, but also an improving effect on creep life, whereas, hafnium and titanium additions have negative strengthening effects on the elevated temperature strength. The effect of varying WC3015 compositions on the mechanical properties, in general, was shown to follow the above conclusions. Titanium additions have been shown to have a severe decreasing effect on creep strength [7].⁵

The additional oxidation resistance or formability gained by titanium additions may for some applications be worth the negative effect on high temperature tensile and creep strength. However, oxidation tests showed that even the heat 216, which combines the highest levels of tungsten, hafnium, and titanium, is not sufficiently oxidation resistant to be used in the bare condition for even short time applications. It was also shown that WC3015 oxidized faster than Cb752 up to 42 min of exposure to 1316°C (2400°F). Thus, WC3015 is not superior to other columbium alloys in providing a better oxidation resistance for one reentry. Therefore, WC3015 must compete with the other primary columbium alloys on the basis of other properties such as formability, joining, and mechanical properties. Significant improvements introduced by tantalum additions to columbium alloys, on ductile-to-brittle transition temperature and on elevated temperature creep, have been demonstrated by FS85. It is believed that substitution of 10 to 15 percent of the hafnium by tantalum, Cb-15W-(15-20)Hf-10Ta-0.1C-Y will provide better ductility, lower DBTT, and higher elevated temperature tensile and creep strengths.

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Marshall Space Flight Center, Alabama 35812
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5. Ibid.

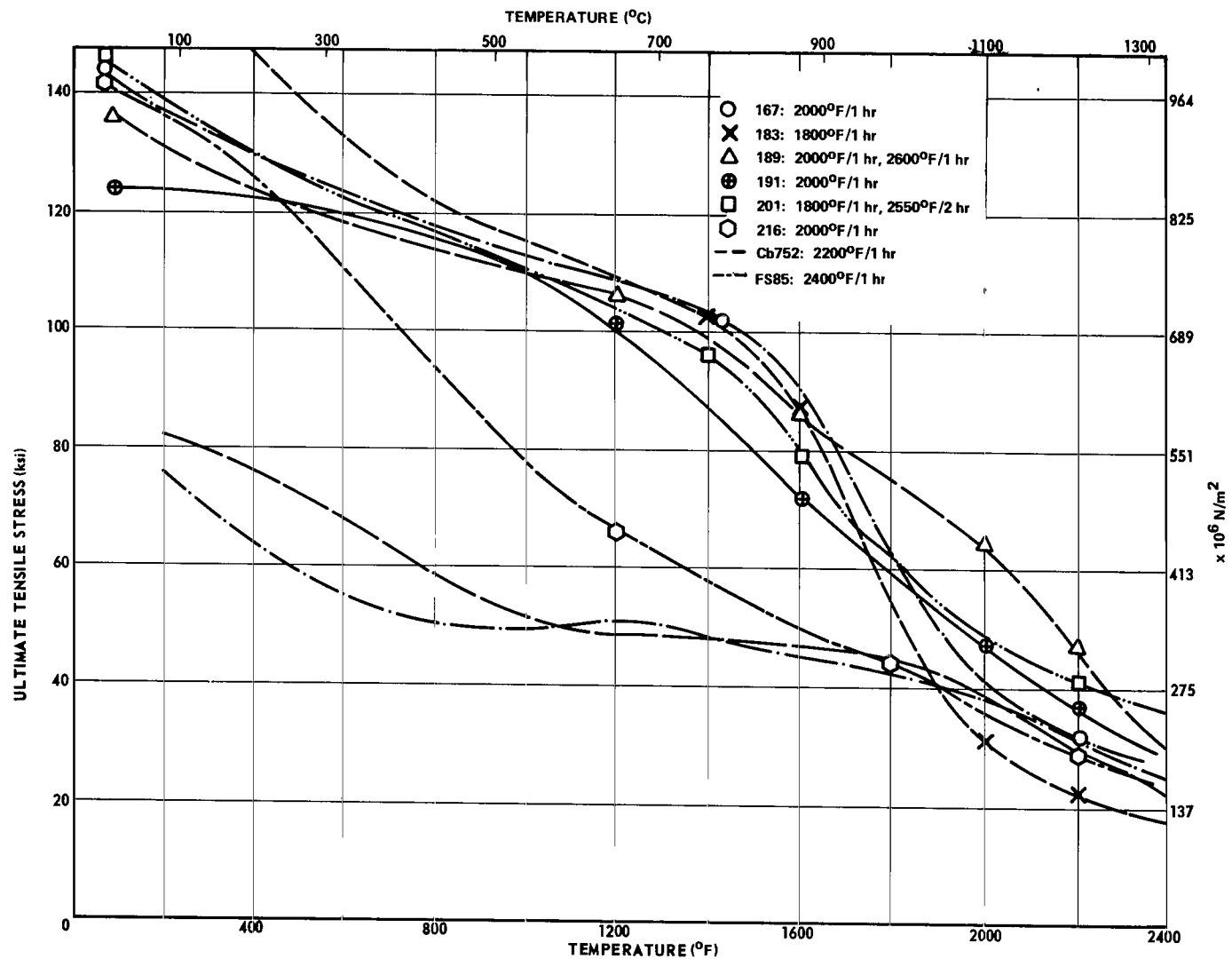


Figure 1. Ultimate tensile strength versus temperature for WC3015 heats and leading columbium alloy candidates.

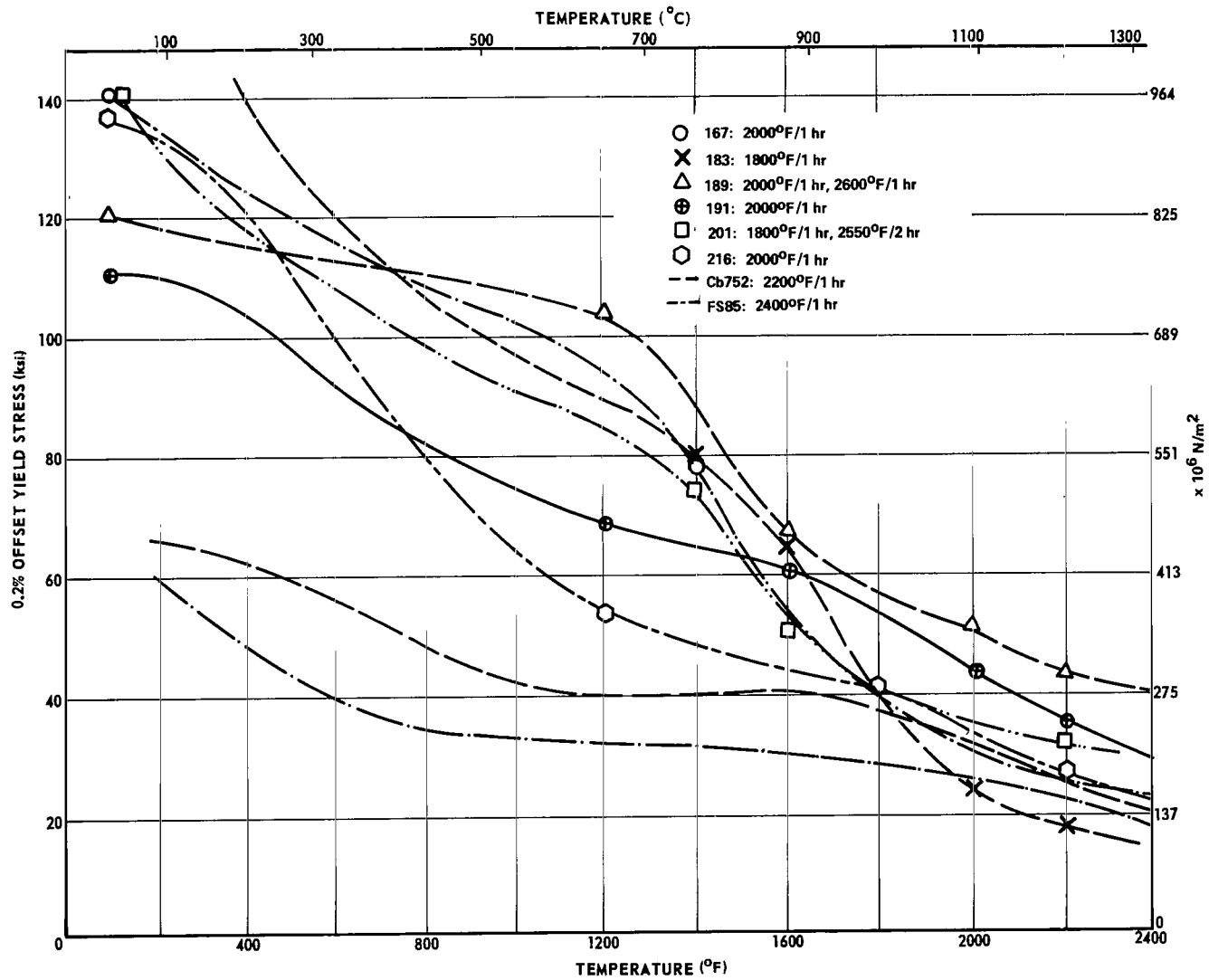


Figure 2. 0.2 Percent yield stress versus temperature for WC3015 heats and leading columbium alloy candidates.

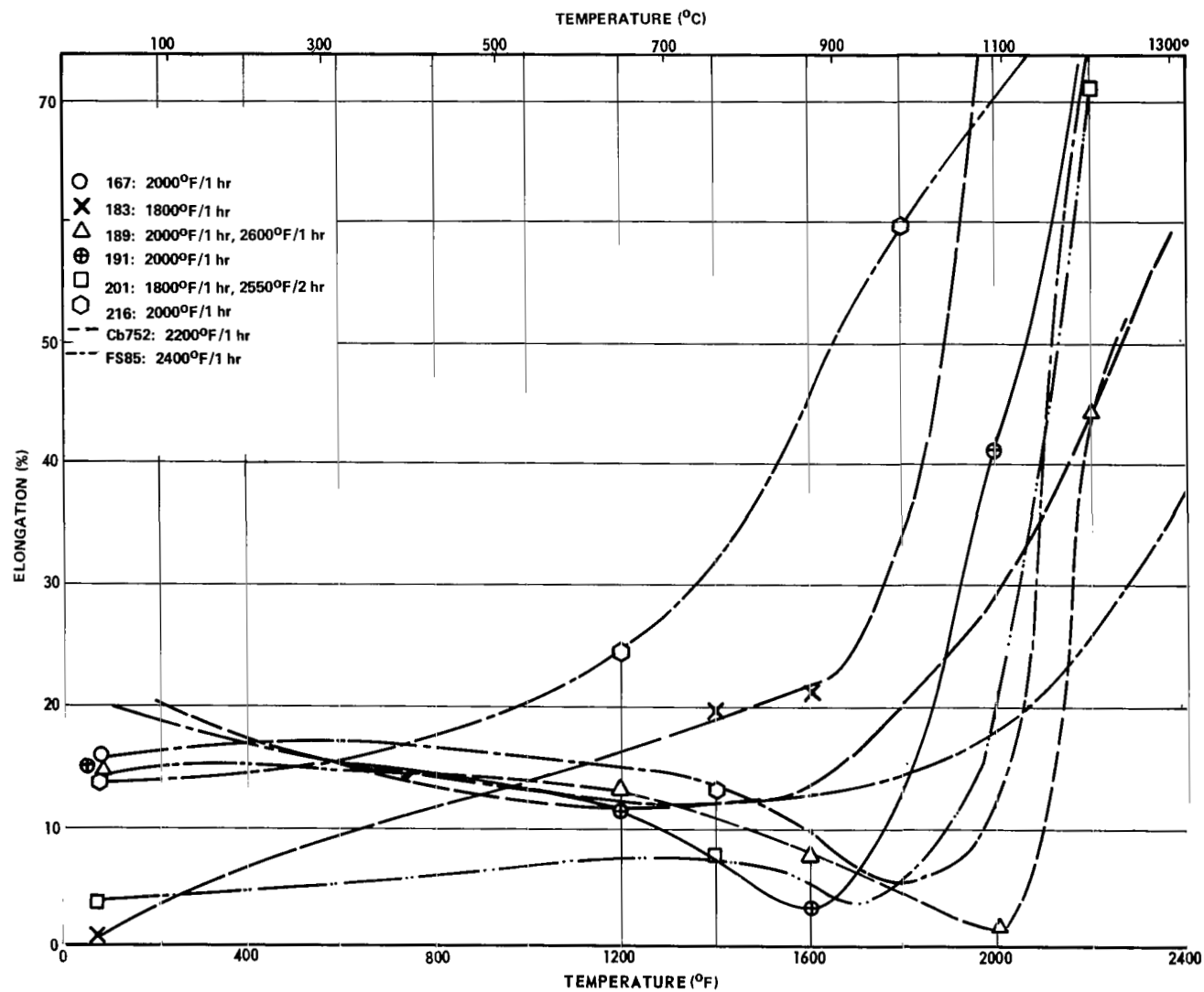


Figure 3. Elongation versus temperature for WC3015 heats and leading columbium alloy candidates.



HEAT 189

MAG 500X



HEAT 191

MAG 500X



HEAT 201

MAG 500X



HEAT 216

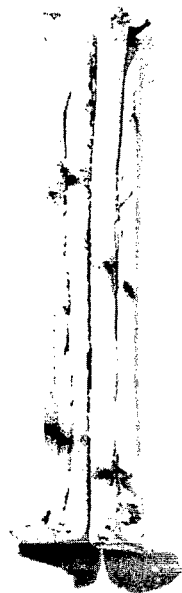
MAG 500X



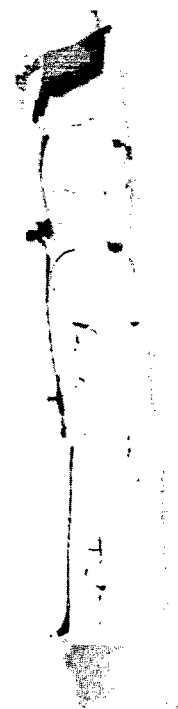
HEAT 230

MAG 500X

Figure 4. Optical photomicrographs for WC3015 heats annealed 1 hr at 1093°C (2000°F).

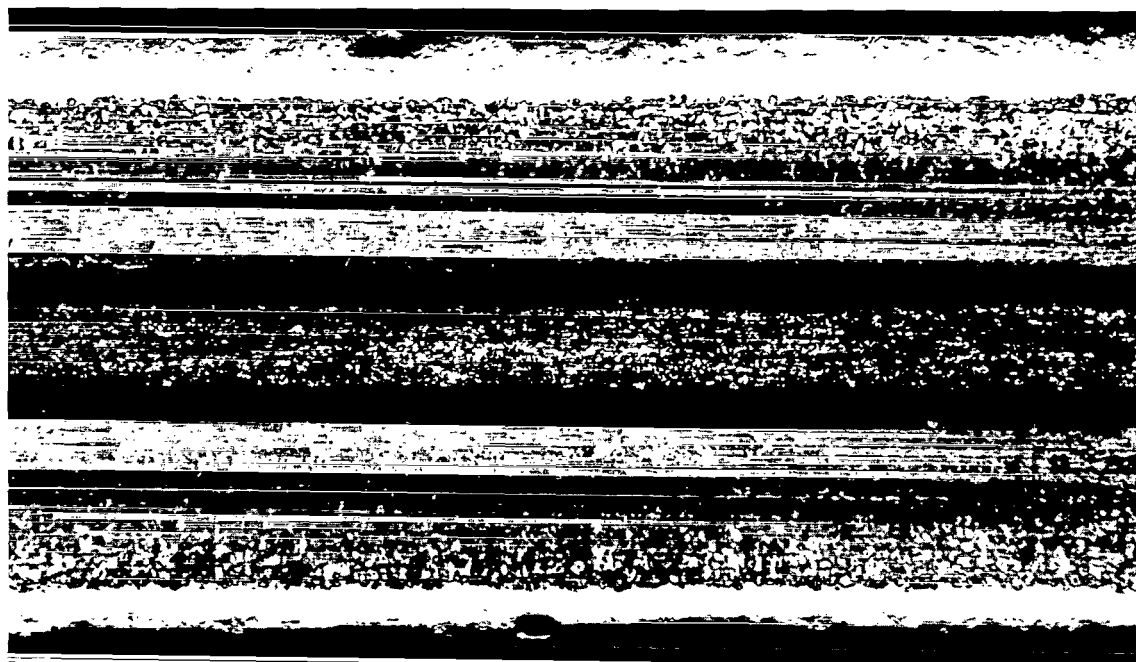


Cb 752

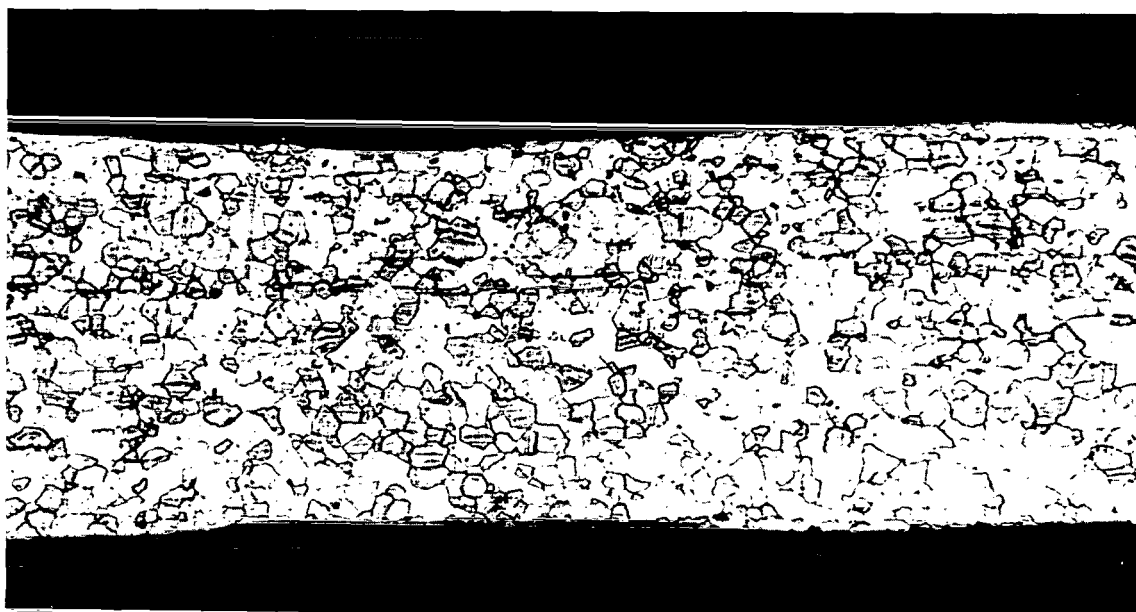


WC 3015

Figure 5. WC3015 and Cb752 samples after 4 hr at 1316°C (2400°F) in still air.



WC3015 (HEAT 216)



Cb752 (HEAT 86D1185)

Figure 6. Photomicrographs showing degree of oxidation for WC3015 and Cb752 after 30 min exposure at 1316°C (2400°F) in still air.

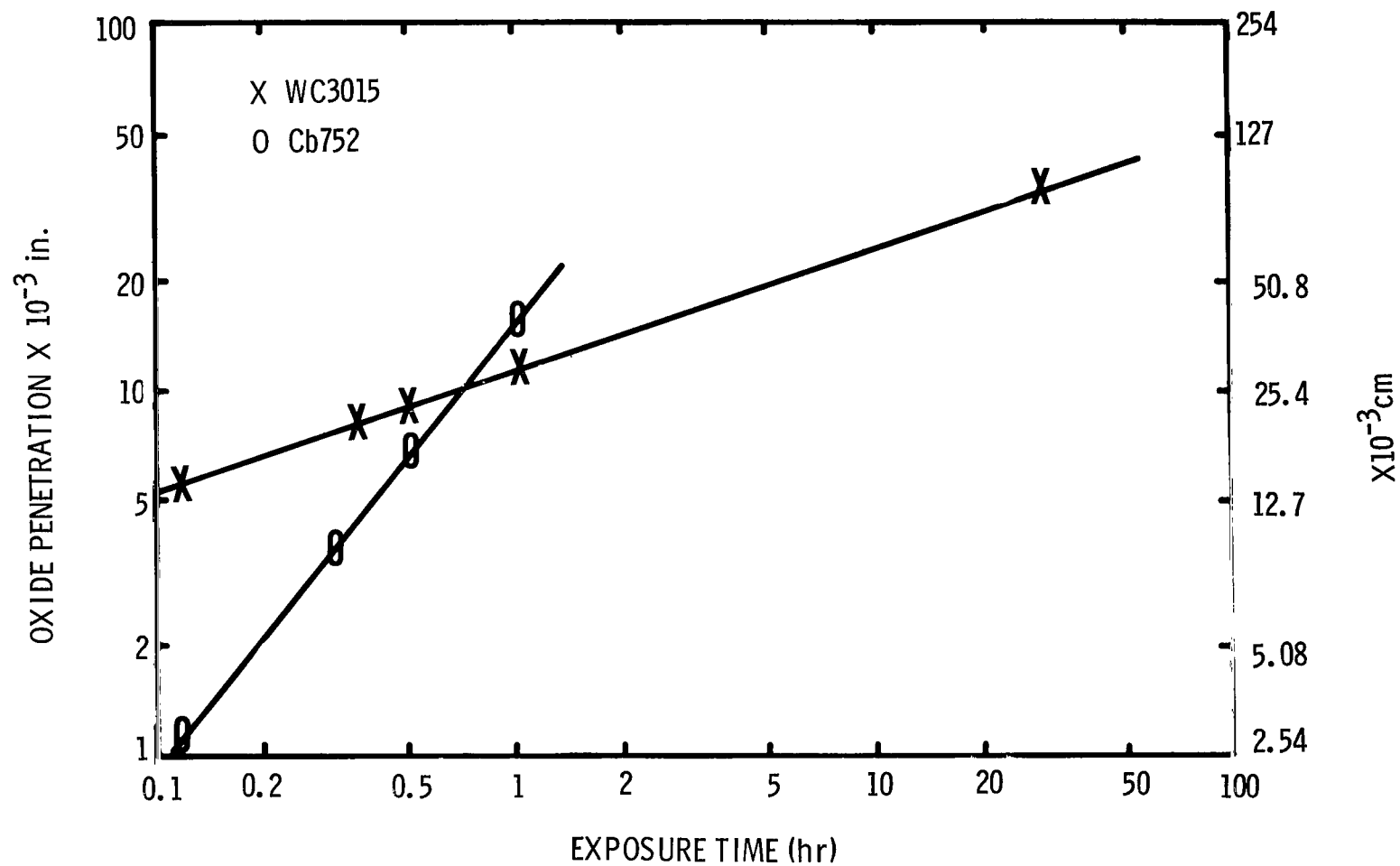


Figure 7. Oxide penetration versus exposure time at 1316°C (2400°F) for WC3015 and Cb752.

TABLE 1. ACTUAL COMPOSITION OF WC3015 HEATS
AND PRIMARY COLUMBIUM ALLOY CANDIDATES

| WC3015 Heat No. | Nominal Composition of Elements | | | | | | | | | |
|-------------------------|---------------------------------|-------|------|------|------|-------------------|------|-----|------|-----|
| | Weight (%) | | | | | Parts Per Million | | | | |
| | Hf | W | Ti | Zr | Ta | C | Y | O | N | H |
| 066 | 27.0 | 14.5 | - | 1.04 | 3.45 | 1020 | - | 120 | 53 | 2.7 |
| 068 | 29.2 | 13.7 | - | 1.03 | 3.58 | 3100 | - | 30 | 80 | 3.1 |
| 137 | 29.2 | 14.3 | 3.9 | 0.95 | <0.1 | 1030 | - | 260 | 38 | 2.7 |
| 145 | 32.0 | 15.9 | - | 1.39 | 0.97 | 800 | - | 270 | 50 | 1.9 |
| 167 | 29.0 | 13.3 | 5.3 | 0.85 | 0.50 | 60 | - | 125 | 30 | 4.0 |
| 183 | 31.5 | 15.0 | 4.47 | 0.80 | 0.70 | 470 | - | 230 | 30 | 2.5 |
| 189 | 28.8 | 15.8 | 0.02 | 0.93 | 0.70 | 880 | - | 270 | 50 | 3.8 |
| 191 | 30.5 | 10.9 | 4.82 | 1.02 | 0.55 | 620 | - | 320 | 72.5 | 3.3 |
| 196 | 27.2 | 13.6 | 4.30 | 1.2 | 0.51 | 470 | - | 240 | 55 | 2.1 |
| 197 | 30.1 | 13.8 | 4.60 | 1.42 | 0.62 | 520 | - | 310 | 60 | 2.6 |
| 201 | 28.2 | 15.4 | 4.27 | 0.94 | 0.55 | 1000 | - | 280 | 35 | 3.6 |
| 216 | 28.5 | 14.4 | 4.66 | 1.20 | 0.65 | 440 | 550 | 120 | 57 | 2.1 |
| 230 | 29.0 | 14.4 | 4.73 | 1.31 | 0.70 | 520 | 300 | 200 | 62 | 2.6 |
| Cb752 (heat 86D1185) | - | 10.45 | - | 2.62 | 0.43 | 25 | - | 135 | 54 | 7 |
| Alloy (Typical) | | | | | | | | | | |
| C129Y | 10 | 10 | - | - | - | 150 | 2000 | 225 | 150 | |
| Cb752 | - | 10 | - | 2.5 | - | 40 | - | 60 | 80 | |
| FS85 | - | 10 | - | 1 | 28 | 40 | - | 60 | 50 | |

TABLE 2. TENSILE PROPERTIES OF EARLY WC3015 HEATS AT ROOM TEMPERATURE

| Heat No. | Composition | Annealing Temperature | | Time (hr) | Diameter | | UTS | | 0.2 Percent Yield Stress | | Elongation Percent 5.08 cm (2 in.) |
|----------|-----------------------------|-----------------------|------|-----------|----------|-------|---------------------------------------|-------|---------------------------------------|-------|---------------------------------------|
| | | (°C) | (°F) | | (cm) | (in.) | (N/m ² × 10 ⁶) | (ksi) | (N/m ² × 10 ⁶) | (ksi) | |
| 066 | 29Hf-14.5W-0.1C | 1316 | 2400 | 6 | 4.13 | 1 5/8 | 654 | 95.3 | - | | <1 |
| | | As Extruded | | | 1.27 | 0.5 | 880 | 128 | 846 | 123 | 5 |
| | | 1316 | 2400 | 6 | 1.27 | 0.5 | 888 | 129 | 840 | 122 | 33 |
| | | 1760 | 3200 | 1 | 1.27 | 0.5 | 840 | 122 | 820 | 119 | 4 |
| 068 | 29Hf-13.5W-0.3C | 1316 | 2400 | 6 | 4.13 | 1 5/8 | 980 | 142 | 880 | 128 | 4 |
| | | As Extruded | | | 1.27 | 0.5 | 902 | 131 | 860 | 125 | 7 |
| | | 1316 | 2400 | 6 | 1.27 | 0.5 | 915 | 133 | 875 | 127 | 27 |
| | | 1649 | 3000 | 1 | 1.27 | 0.5 | 875 | 127 | 827 | 123 | 4 |
| 075 | 30Hf-11W-5Ti-0.3C | 1316 | 2400 | 1 | 4.13 | 1 5/8 | 799 | 116 | - | | <1 |
| 078 | 30Hf-13.5W-5Ti-0.1C.047A1 | 1316 | 2400 | 6 | 4.13 | 1 5/8 | 799 | 116 | - | | <1 |
| | | As Extruded | | | 1.27 | 0.5 | 935 | 136 | 880 | 128 | 13 |
| | | 1316 | 2400 | 6 | 1.27 | 0.5 | 915 | 133 | 888 | 129 | 28 |
| | | 1760 | 3200 | 1 | 1.27 | 0.5 | 909 | 132 | - | | <1 |
| 081 | 30Hf-14.5W-4Ti-0.3C-0.060A1 | 1316 | 2400 | 6 | 4.13 | 1 5/8 | 604 | 87.6 | - | | <1 |

TABLE 3. EFFECT OF ANNEALING TEMPERATURE ON TENSILE PROPERTIES OF WC3015 HEATS^a

| Heat No. | Annealing Temperature | | Time (hr) | Room Temperature | | | | | 1093°C (2000°F) | | | | | 1204°C (2200°F) | | | | |
|----------|--------------------------|------|-----------|---------------------------------------|-------|---------------------------------------|-------|--------------------|---------------------------------------|-------|---------------------------------------|-------|--------------------|---------------------------------------|-------|---------------------------------------|-------|--------------------|
| | | | | UTS | | 0.2 Percent Yield Stress | | Elongation Percent | UTS | | 0.2 Percent Yield Stress | | Elongation Percent | UTS | | 0.2 Percent Yield Stress | | Elongation Percent |
| | (°C) | (°F) | | (N/m ² × 10 ⁷) | (ksi) | (N/m ² × 10 ⁷) | (ksi) | | (N/m ² × 10 ⁷) | (ksi) | (N/m ² × 10 ⁷) | (ksi) | | (N/m ² × 10 ⁷) | (ksi) | (N/m ² × 10 ⁷) | (ksi) | |
| 167 | 982 | 1800 | 1 | 107 | 156 | 103 | 149 | 4 | - | - | - | - | - | - | - | - | - | - |
| 167 | 1093 | 2000 | 1 | 98.5 | 143 | 96.3 | 140 | 16 | - | - | - | - | - | 21.8 | 31.6 | 17.6 | 26.3 | 86 |
| 167 | 1399 | 2550 | 2 | 53.7 | 78.6 | - | - | <1 | - | - | - | - | - | 30.6 | 44.3 | 18.5 | 26.8 | 1 |
| 183 | 982 | 1800 | 1 | 137 | 199 | 133 | 193 | 1 | 21.4 | 31 | 16.5 | 24 | 122 | 15.6 | 22.6 | 13.4 | 19.5 | 110 |
| 183 | 982 1800 + 1399 2550 | | 1 2 | - | - | - | - | - | - | - | - | - | - | 31.4 | 45.5 | 26.5 | 38.5 | 27 |
| 201 | 982 | 1800 | 1 | 112 | 162 | 110 | 159 | 13 | - | - | - | - | - | - | - | - | - | - |
| 201 | 982 1800 + 1093 2000 | | 1 1 | 102 | 148 | - | - | 19 | - | - | - | - | - | - | - | - | - | - |
| 201 | 982 1800 + 1204 2200 | | 1 1 | 107 | 156 | 90.7 | 132 | 17 | - | - | - | - | - | - | - | - | - | - |
| 201 | 982 1800 + 1399 2550 | | 1 2 | 101 | 146 | 96.2 | 140 | 4 | - | - | - | - | - | 28.2 | 41 | 23.4 | 34 | 74 |
| 201 | 982 1800 + 1427 2600 | | 1 1 | 97.6 | 142 | 93.5 | 136 | 11 | 38.8 | 56.3 | 35.7 | 51.6 | 2 | 27.6 | 40 | 26.7 | 38.7 | 56 |
| 201 | 982 1800 + 1427 2600 | | 1 2 | 103 | 149 | 91.5 | 133 | 16 | 40.3 | 58.4 | 35.3 | 51.2 | 12 | 30 | 43.5 | 25.1 | 35 | 100 |
| 216 | 1093 | 2000 | 1 | 98.5 | 143 | 95.0 | 138 | 14 | - | - | - | - | - | 20.7 | 30 | 18.6 | 27 | 110 |
| 216 | 1093 2000 + 1427 2600 | | 1 1 | 97.0 | 141 | 99.4 | 130 | 16 | 35.8 | 52 | 33.1 | 48 | 2 | 27.6 | 40 | 25.5 | 37 | 40 |
| 216 | 1093 2000 + 1427 2600 | | 2 2 | 96.3 | 140 | 87.4 | 127 | 16 | 37.7 | 54.6 | 35.0 | 50.7 | 1 | 36.2 | 38 | 22.7 | 33 | 63 |

a. Sheet, 0.508 - 0.89 mm (0.020 - 0.035 in.) thickness.

TABLE 4. BEND ANGLE VERSUS TEMPERATURE FOR WC3015 HEATS^a

| Heat No. | Annealing Temperature | | Time (hr) | Temperature | | Bend Angle (deg) |
|----------|-----------------------|--------|-----------|-------------|------|------------------|
| | (°C) | (°F) | | (°C) | (°F) | |
| 066 | 982 | 1800 | 1 | 21 | 69.8 | 45 (1t) |
| | 982+ | 1800 + | 1 | 21 | 69.8 | 80 (1t) |
| | 1093 | 2000 | | 93 | 200 | 180 (1t) |
| | 1316 | 2400 | 2 | 21 | 69.8 | 90 (4t) |
| | | | | 21 | 69.8 | 100 (4t) |
| 068 | 1316 | 2400 | 6 | 21 | 69.8 | 12 (1t) |
| | 1204 | 2200 | 1 | 21 | 69.8 | 95 (1t) |
| 167 | 1093 | 2000 | 1 | 316 | 600 | 160 (1t) |
| | 1204 | 2200 | 1 | 316 | 600 | 160 (2t)* |
| | 1316 | 2400 | 2 | 21 | 69.8 | 0 (1t)* |
| | 1204+ | 2200 + | 1 | 21 | 69.8 | 0 (1t) |
| | 1316 | 2400 | | | | |
| 183 | 982 | 1800 | 1 | 21 | 69.8 | 90 (1t) |
| | | | | 21 | 69.8 | 105 (4t) |
| 189 | 1093 | 2000 | 1 | -127 | -197 | 123 (3t)* |
| 191 | 1093 | 2000 | 1 | -127 | -197 | 125 (3t)* |
| 197 | 1093 | 2000 | 1 | 21 | 69.8 | 110 (1t) |
| | 1399 | 2550 | 1 | 149 | 300 | 100 (1t) |
| 201 | 1093 | 2000 | 1 | -127 | -197 | 50 (3t)* |
| 216 | 1093 | 2000 | 1 | -127 | -197 | 139 (3t) |
| 216 | 1316 | 2400 | 1 | -73 | -100 | 22 (1t) |

^a Samples thickness 0.508 mm (0.020 in.) except those marked with * which were 0.762 to 1.016 mm (0.030 to 0.040 in.)

TABLE 5. WEIGHT AND TENSILE STRENGTH CHANGES FOR WC3015 AND Cb752
AFTER 30 MIN OF EXPOSURE TO 1316°C (2400°F) IN STILL AIR

| Alloy and Heat No. | Annealing Temperature | | Time (hr) | Condition | Weight (gm) and Weight Change (%) | UTS | | 0.2 Percent Yield Stress | | Elongation Percent 5.08 cm (2 in.) |
|--------------------------|--------------------------|------|--------------|-------------------|--|--|-------|--|-------|--|
| | (°C) | (°F) | | | | (N/m ² × 10 ⁶) | (ksi) | (N/m ² × 10 ⁶) | (ksi) | |
| WC 3015 (heat 216) | 1093 | 2000 | 1 | As Received | 12.9898 | 970 | 141 | 930 | 135 | 22 |
| | | | | Air Cooled | +3.6% | 69.3 | 9.9 | - | - | <1 |
| | | | | Furnace Cooled | +2.22% | 154 | 22.4 | - | - | <1 |
| Cb752 (heat 86D1185) | 1204 | 2200 | 1 | As Received | 11.6718 | 583 | 84.7 | 493 | 71.5 | 24 |
| | | | | Air Cooled | Fractured | - | - | - | - | - |
| | | | | Furnace Cooled | -50% | 231 | 33.6 | - | - | <1 |

TABLE 6. OXIDATION DATA AT 1204°C (2200°F)/100 MIN FOR
SEVERAL WC3015 HEATS, C129Y AND Cb752 WITH A
0.117 × 6.35 mm (0.004 × 0.25 in.) COATING DEFECT

| Alloy | Coating | Coating Loss | | Oxygen Affected Zone | |
|--------|---------|--------------|---------|----------------------|--------|
| | | (mm) | (in.) | (mm) | (in.) |
| C129Y | VH109 | 0.2795 | 0.011 | 0.39 | 0.0153 |
| Cb752 | VH109 | 0.254 | 0.010 | 0.493 | 0.0194 |
| WC3015 | | | | | |
| Ht 189 | VH112 | 0.152-0.178 | 0.006-7 | 0.175 | 0.0069 |
| Ht 191 | VH112 | 0.152 | 0.006 | 0.198 | 0.0078 |
| Ht 216 | VH112 | 0.152 | 0.006 | 0.175 | 0.0069 |
| Ht 201 | VH112 | 0.178 | 0.007 | 0.213 | 0.0084 |

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